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Accurate Measurement of Velocity and Acceleration of Seismic Vibrations near Nuclear Power Plants

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Abstract

In spite of all prerequisite geological study based precautions, the sites of nuclear power plants are also susceptible to seismic vibrations and their consequent effects. The effect of the ongoing nuclear tragedy in Japan caused by an earthquake and its consequent tsunami on March 11, 2011 is currently beyond contemplations. It has led to a rethinking on nuclear power stations by various governments around the world. Therefore, the prediction of location and time of large earthquakes has regained a great importance. The earth crust is made up of several wide, thin and rigid plates like blocks which are in constant motion with respect to each other. A series of vibrations on the earth surface are produced by the generation of elastic seismic waves due to sudden rupture within the plates during the release of accumulated strain energy. The range of frequency of seismic vibrations is from 0 to 10 Hz. However, there appears a large variation in magnitude, velocity and acceleration of these vibrations. The response of existing or conventional methods of measurement of seismic vibrations is very slow, which is of the order of tens of seconds. A systematic and high resolution measurement of velocity and acceleration of these vibrations are useful to interpret the pattern of waves and their anomalies more accurately, which are useful for the prediction of an earthquake. In the proposed work, a fast rotating magnetic field (RMF) is used to measure the velocity and acceleration of seismic vibrations in the millisecond range. The broad spectrum of pulses within one second range, measured by proposed method, gives all possible values of instantaneous velocity and instantaneous acceleration of the seismic vibrations. The spectrum of pulses in millisecond range becomes available which is useful to measure the pattern of fore shocks to predict the time and location of large earthquakes more accurately. Moreover, instead of average, the peak values of these quantities are helpful in proper design of earthquake resistant nuclear power plants, buildings and structures. The proposed measurement scheme is successfully tested with a microprocessor based rocking vibration arrangement and the overall performance is recorded at dynamic conditions.

Keywords: Rotating magnetic field based seismometer; accelerometer; seismic vibrations; prediction of earthquakes; synchro

1. Introduction

Enormous destruction and economic losses are common due to earthquakes and landslides provoked by geological instabilities and rock impacts [1]. The earthquake of Japan on March 11, 2011 has raised alarm worldwide regarding nuclear power generation. The earth quake in Haiti on January 12, 2010 had killed more than 230,000 people. The earth quake of Sumatra (Tsunami) on December 26, 2004 killed more than 300,000 people in 11 countries. Therefore, the prediction of location and time of large earthquakes has regained a great importance. A high resolution measurement of velocity and acceleration of fore shocks helps more accurate prediction of earthquakes [2-3]. The instruments like seismometers and accelerometers, used for monitoring seismic vibrations have been mainly developed in view of measuring only one parameter which is the acceleration [4]. Furthermore, the present seismometers fail to

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record the peak values of acceleration, displacement, speed, rise time caused by strong motions in the critical area near field of strong earthquakes, with good accuracy [5]. Hence due to poor resolution, the peak values of seismic wave's parameters are missed, which causes problems in the consistent design of nuclear power plants, industrial plants and buildings, resistant to strong earthquakes. This fact has been demonstrated by the destruction of heavy constructions in the recent strong earthquakes. Therefore, for a more consistent design of buildings, it would be an advantage to measure directly the seismic waves acting on the buildings.

It is well known fact that a highly reliable prediction method of earthquakes does not exist [4]. This has been demonstrated from the destruction of big earthquakes (Friuli, Mexico City 1985, Aegion 1995, Northridge 1994, Kobe 1995, Umbria 1997, Turkey 1999, Sumatra (Tsunami), 2004, Haiti 2010 and Japan 2011). Some empirical attempts to predict the earthquakes were done in Greece based on the change of electric current in the soil [6 -10]. However, the prediction is too vague and no feasible decision such as to evacuate the population of a certain area for a given period of time, can be made [11-12]. Also attempts about the prediction of earthquakes were done in Japan, based on the change of chloride and sulphur content in mineral water [13-14]. This technique is not only expensive but also allows us to move the clock back on time and search for potential earthquake precursors [15]. A number of methods, based on the measurement of velocity and acceleration of seismic vibrations are also reported in the literature. However, these methods are still slow and less accurate, as the resolution of measurement of seismic vibrations is of the order of tens of seconds. Hence these methods do not give high resolution (less than one second) data for better prediction [16-20].

In the proposed method, a fast rotating magnetic field (RMF) is used to generate an emf in a rotor circuit which depends upon the motion and/or vibration of the rotor [21]. A microprocessor based vibration generation system is developed to generate rocking motion and vibrations. The vibration system vibrates the rotor of synchro back and forth, which ultimately varies the frequency and voltage in the rotor circuit. It gives the spectrum of pulses which corresponds to the velocity of seismic vibrations. As the rotation of magnetic field is kept faster (several times) that of the rotor, the measurement of instantaneous velocities, of these vibrations becomes extremely fast. The fast measurement of velocity and acceleration of these vibrations give high resolution of measurand which would be helpful in more accurate prediction of earthquakes and designing structures.

2. Theory

A synchro has a three-phase stator winding and a winding on the rotor. The rotor output is received using two slip ring arrangements. If a three-phase winding of a synchro is energized by a three-phase input voltage, the speed (revolution) of a rotating magnetic field in the air-gap of a stator, produced by a balanced three-phase ac current is given by

$$n_s = \frac{120\, f_s}{P} \tag{1}$$

Where P is number of poles and f_s is frequency of the stator input voltage or current, in Hz.
If the rotor of a synchro is rotating at n_r rpm, the relative speed or the slip is $(n_s - n_r)$, in the direction of n_s. However, if it rotates in opposite direction, the slip becomes $(n_s + n_r)$. The frequency of the induced emf in the rotor circuit is given by

$$f_r = \frac{(n_s \mp n_r)P}{120} \tag{2}$$

and,

$$f_r = f_s \mp \frac{n_r\, P}{120} \tag{3}$$

Since, the supply frequency (f_s) and the number of stator poles (P) are constant, therefore, the frequency of the induced emf in the rotor circuit varies linearly with the variation of the rotor speed, n_r. When the rotor of the synchro (rotating member) is standstill, the synchro acts as a transformer. Therefore the frequency of rotor emf (f_r), is same as that of stator ($f_r = f_s$). However, when the rotor rotates, the frequency is proportional to the slip ($n_s \mp n_r$), where n_s is constant. In this case the speed or frequency of the rotor corresponding to the seismic vibrations which is in the range of few Hz only, while the frequency of rotating magnetic field is 50 Hz. Therefore the measurement becomes very fast and the resolution becomes very high.

3. Realization

In the proposed technique, for the measurement of velocity and acceleration of seismic vibrations, a synchro is used whose rotor is attached with the vibration system (Fig. 1). The three-phase stator winding of the synchro, S is energized by a 50 Hz voltage signal from a stable arbitrary function generator (FG). This signal is supplied to a centre-tapped transformer whose output is applied to a single-phase to three-phase conversion circuit, consisting an RC network (R=100 kΩ and C = 0.1μF), to generate a balanced three-phase, 50 Hz voltages: V_{a1}, V_{b1}, and V_{c1} (Fig. 2). These three voltages are attenuated to a value of about 100 mV (V_{a2}, V_{b2}, and V_{c2}), before feeding into three audio power amplifiers (LM 384N). The outputs of these three amplifiers, V_A, V_B and V_C (Fig. 3a), are applied to the stator winding of synchro, S to produce a sinusoidal signal, V_r with frequency, f_r in the rotor winding of synchro (Fig. 3b).

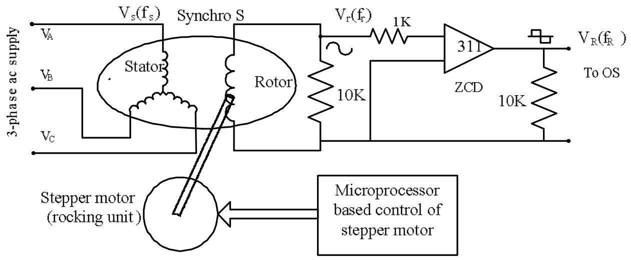


Fig. 1 Microprocessor based vibration generation and measurement setup.

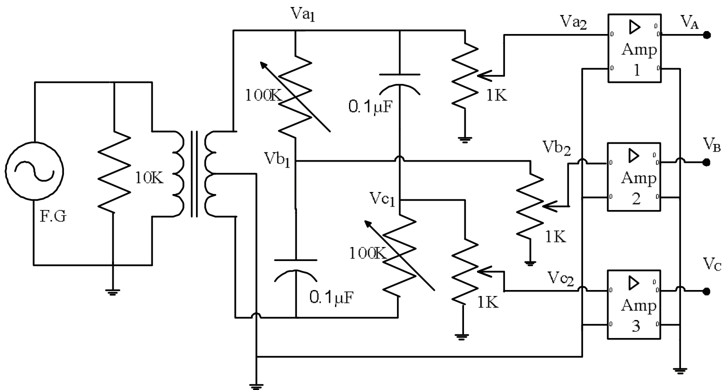
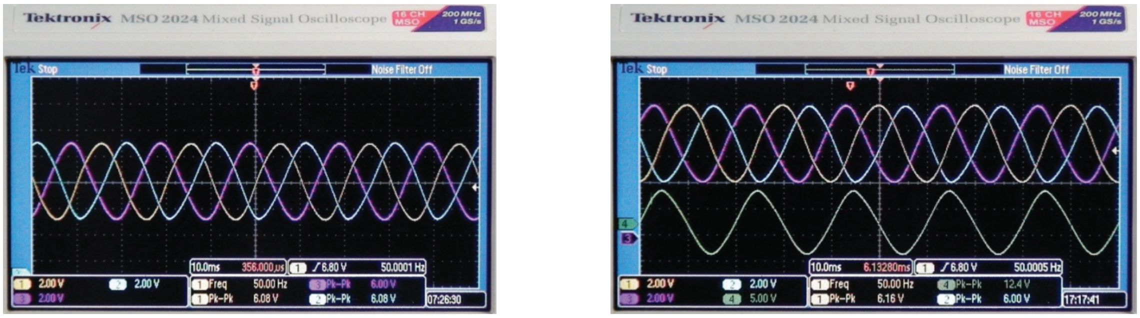


Fig. 2 Single-phase to three-phase voltage conversion system.

4. Experimental Results and Discussion

The seismic waves are generated by aircraft impacts, collapse of a large building, underground nuclear explosion and exploding dynamites. But these vibrations are not feasible or allowed for conducting tests. Another method which is generally used is to place a small brick work over a metal platform. That metal platform is given large vibrations using heavy electrical machinery. The instruments are attached with the brick work to study the behaviour of vibrations. These instruments are connected to computers in order to record the output. Another method of seismic vibration generation being used in a research institution is by a Shake Table [22]. But these methods are very costly, difficult to realize, non portable, inaccurate and require large installation area and huge seismographic stations.

Here, to realize the vibrations like seismic vibrations, a microprocessor based lab model is developed. The microprocessor is programmed to vibrate the stepper motor to generate the vibrations in the range of -50 cm/s to +50 cm/s, with a frequency of about 2 Hz, similar to the seismic vibrations (Fig. 8a-b). The stepper motor is coupled to the rotor of a synchro, S. The vibrations generated by the stepper motor are transmitted to the rotor of synchro, S. Therefore, the frequency of rotor voltage changes and a pulse train of variable pulse-width is recorded which corresponds to the instantaneous velocity of vibrations. The proposed system can be simply coupled with the conventional standard spring attachment system to measure the actual seismic vibrations.



(a) (b)

Fig. 3. (a) Measured waveforms V_A, V_B, V_C at the output of power amplifiers (CH#1, CH#2 and Ch#3) (b) Measured three phase voltages, V_A, V_B, V_C at stator winding of synchro (CH#1, CH#2 and Ch#3). V_r, f_r (CH#4)

4.1 When the vibration system is stationary

As long as the vibrating system is stationary, the speed of rotor of synchro, S is zero. The synchro acts as a transformer. The frequency of rotor emf, f_r is equal to the frequency of stator voltage, f_s. The signal V_r is now applied to a fast voltage comparator as a zero crossing detector (ZCD). It produces a rectangular waveform, V_R of frequency, f_R where $f_R = f_r$, as shown in Fig. 4. The positive going transition (PGT) of signal, V_R is used to trigger a one-shot mono-stable multi-vibrator (OS) as shown in Fig. 5. It gives an output, Q of a constant positive width equal to 10 ms. The output of gate G-1 remains high as the positive width of signal V_R is equal to negative width of Q´. This is also given by

$$f_r = f_s \mp \frac{n_r P}{120} \tag{3}$$

$$\text{Also,} \quad T_{WG-} = T_{WR+} - T_{WQ-} \tag{4}$$

Where,
f_R = Frequency of signal V_R at the output of ZCD ($f_R = f_r$).
f_s = Frequency of induced emf (V_s) of stator of synchro.
T_R = Time period of the signal V_R at the input of OS.
T_{WR+} = Positive width of the signal V_R.
T_{WQ+} = Positive width of signal Q
T_{WQ-} = Negative width of signal Q´
T_{WG-} = Negative width of the pulse at the output of G-1

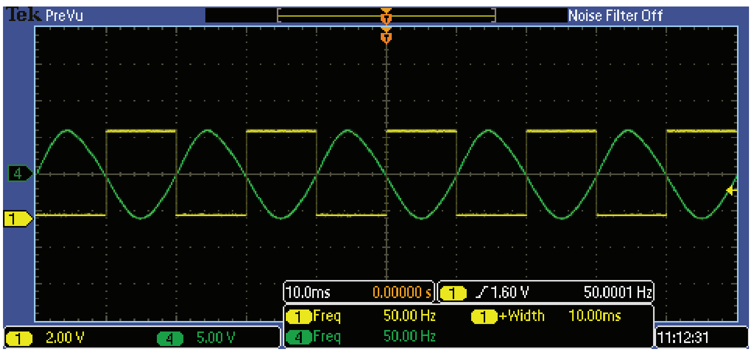


Fig. 4. Measured output of rotor, V_r, f_r of synchro, S (Ch#4) and Output of ZCD, V_R, f_R (Ch#1) at 50 Hz.

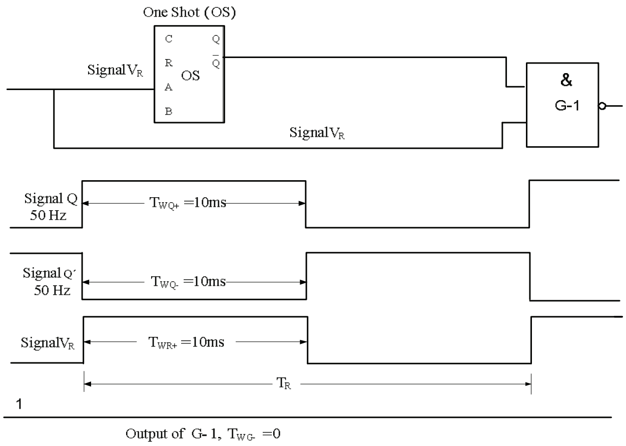


Fig. 5. Waveforms of signals, V_R, Q, Q´ and output T_{WG-}, when the vibrating system is stationary.

When the vibrating system is stationary.

$f_R = f_s = 50$ Hz

$T_R = (1/f_R) = 20$ ms

$T_{WR+} = (T_R / 2) = (1/2f_R) = 10$ ms

$T_{WQ-} = 10\text{ms} = 0.01$ seconds

$T_{WG-} = T_{WR+} - T_{WQ-}$

$T_{WG-} = 10 - 10 = 0$

Therefore output of gate G-1= 1

The waveforms V_r, V_R, Q´ and T_{WG-} are also shown in the DSO records (Fig. 6).

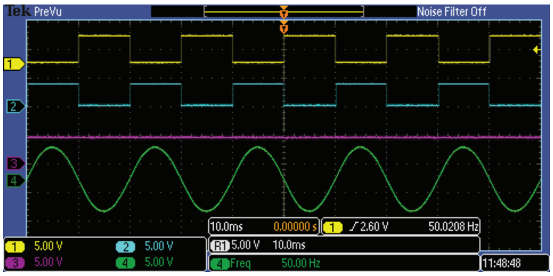


Fig. 6. Measured output of ZCD, V_R (Ch#1), output of OS Q´ (Ch#2), output of gate G-1, T_{WG-} (Ch#3) at 50Hz and output of synchro Vr (Ch#4) when the vibrating system is stationary.

4.2 When the system starts vibrating

The rotor of the synchro moves back and forth due to its attachment with the vibrating body (stepper motor). The RMF revolves in the air gap at a very fast speed of 3000 rpm for a 50 Hz, 2 pole machine (synchro S). Even a very small angular movement of rotor (one tenth of a radian per second) generates an emf, of frequency, f_r in the rotor circuit which is higher or lower than 50 Hz. A negative pulse appears within 20 ms, for every instantaneous change in the movement of rotor, whose width is proportional to the velocity of the vibration (Fig. 7). The associated time period T_R, (or $1/f_R$) and hence the positive width T_{WR+} of signal, V_R at the output of ZCD varies instantaneously. The PGT of V_R triggers OS to produce a signal, Q and its compliment Q´ with stable positive and negative widths of 10 ms (T_{WQ+} and T_{WQ-} respectively). When the signals V_R and Q´ are applied to G-1, a pulse, T_{WG-} with a negative width is generated at its output on every trailing edge of signal V_R (Figs. 8 and 9). The width of these pulses depends on the instantaneous speed of rotor of synchro, S (or instantaneous velocity of vibration of vibrating system) at different instants of time. The pulse with maximum negative width is proportional to peak velocity of vibration (V_M). The calculations for the measurement of velocity of vibrations with various parameters are given by.

$$f_r = f_s \mp \frac{n_r P}{120} \qquad (3)$$

The pulse width T_{WG-} of instantaneous pulses are given by (4)

$$T_{WG-} = T_{WR+} - T_{WQ-} \quad (4)$$

$$T_{WG-} = (1/2f_R) - 0.01 \quad (5)$$

$$f_r = \frac{1}{0.02 + 2T_{WG-}} \quad (6)$$

From (3) and (6), the instantaneous speed n_r corresponding to any pulse width obtained at the output of gate G-1 is given by

$$\frac{1}{0.02 + 2T_{WG-}} = f_s - \frac{n_r P}{120} \quad (7)$$

For, P = 2 and f_s = 50 Hz, from (7),

$$n_r = 3000 - \frac{60}{0.02 + 2T_{WG-}} \quad (8)$$

The instantaneous velocity (V) of vibrations of the vibrating system is given by

$$V = \omega r$$

$$V = \frac{2\pi \times n_r}{60} r \quad (9)$$

where,

ω = angular speed of rotor of synchro, S in radian per second.

r = radius of rotor of synchro = 0.912 cm

Now from (9), (8) and (10)

$$V = 0.0955 \times n_r \quad (10)$$

and $$V = 286.628 - \frac{5.73}{0.02 + 2T_{WG-}} \quad cm/\sec \quad (11)$$

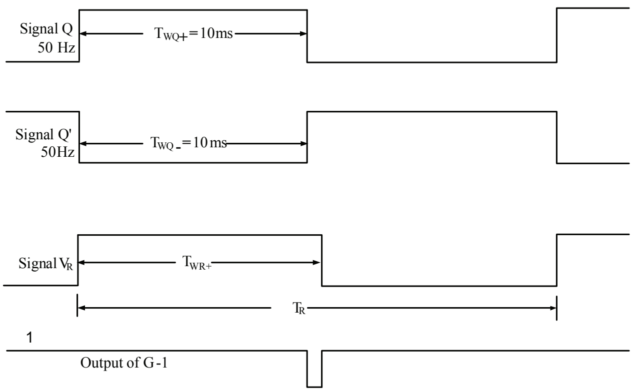


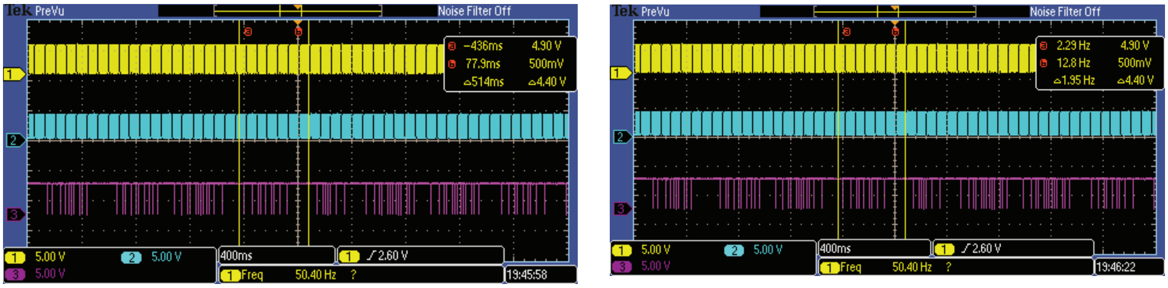
Fig. 7. Waveforms of signals V_R, Q, Q´ and output T_{WG-}, when vibration is started.

S.No.	T_{WG-} (μs) = T_{WR+} - T_{WQ-}	Velocity of Vibrations (cm/s)	Acceleration (cm/s^2)
1	0	0	0
2	153.66	4.29	214.5
3	360	9.94	282.5
4	455	12.45	125.5
5	520	14.15	85
6	1000	26.03	594
7	1600	39.52	306
8	554	-15.02	-225
9	400	-11	-201
10	320	-8.86	-107
11	160	-4.49	-218.5

Table 1: Results of the seismic vibration measurement

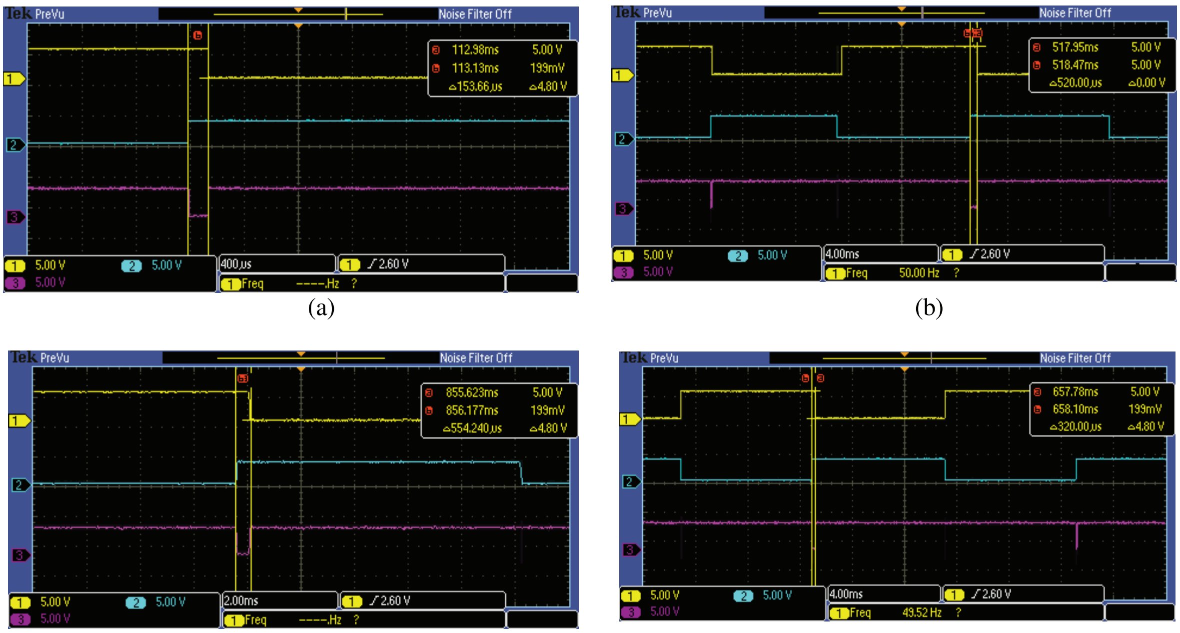
A spectrum with variations of velocity and acceleration of vibrations is observed and recorded by DSO (Figs. 8 and 9). The results are also tabulated in table 1. It shows a significant variation, even within one second, which is normally not sensed and recorded by the conventional seismic vibration measurement systems. The spectrum of one second provides all possible instantaneous velocity and acceleration of seismic vibrations with 20 ms resolution. Hence the measurement for the pattern of vibration becomes very fast and accurate.

When the output of gate G-1 is passed through an averaging circuit and amplifier, a dc voltage is obtained corresponding to the width of these pulses. This directly gives the value of average velocity of vibrations in terms of voltage. The instantaneous values of acceleration of these vibrations are observed by the difference of velocities of two consecutive pulses.



(a) (b)

Fig. 8a-b. Output of ZCD (Ch#1), output of OS (Ch#2) and output of gate G-1 (Ch#3) in roll mode at 400ms.



(a) (b) (c) (d)

Figs. 9a-d. Measured Output of ZCD (Ch#1), output of OS (Ch#2) and output of gate G-1 (Ch#3).

The sensitivity of the proposed method is 3.25×10^{-5} s^2 per cm, obtained as a ratio of infinitesimal change in pulse width and angular motion of the rotor of synchro. The accuracy of the method may be affected by the variation in frequency generated by the function generator. Here, we have used a very high resolution, arbitrary/function generator (Tektronix, AFG-2022 B) with an accuracy (Stability) of ± 1ppm ± 1µHz, 0 °C to 50 °C. Therefore, our apparatus is sufficiently accurate for the proposed instrumentation. The noise level introduced in the apparatus by the power amplifiers (LM384N) is removed by connecting capacitors of high values (4700 µF) at different stages. However, the ambient noise by electromagnetic interference may change the level of output signal at zero crossing point of comparator, which may be taken care of by properly shielding the whole apparatus. The ambient noise in the common wire (ground terminal) and temperature variation of device (LM 311) may also cause the voltage offset in the comparator. This may cause a variation in the pulse width of signal generated by ZCD. Therefore an instrument grade, comparator (LM 311) is used, which is quite immune to spurious oscillations [23]. Hence the accuracy of the measurement system is enhanced.

5. Conclusions

A novel synchro and RMF based seismic vibration measurement technique is proposed. It provides fast measurement of seismic vibrations with high accuracy and resolution. The rotor output of synchro is used to sense the instantaneous variation of velocity of seismic vibrations. A microprocessor based system is used to generate the vibrations in the range of -50 cm/s to +50 cm/s, with a frequency of about 2 Hz. The vibrations change the frequency of induced emf in the rotor circuit which is detected in terms of pulses of different pulse width. The output varies like a pulse modulated signal. The spectrum of pulses shows the measurement of instantaneous velocity of vibration. An analog output (in mV) for the velocity of the vibration is also measured by the output of the gate G-1 using a separate amplifier circuit. The conventional systems give the velocity of vibrations in the range of seconds, while the proposed method measures the vibrations with a resolution of 20 ms. Hence it easily captures those peaks of vibration which are missed by conventional measurement systems due to their poor resolution. Thus, fast measurement of velocity and acceleration of vibrations from the proposed system will help in the prediction of earthquakes and for proper design of earthquake resistant nuclear power plants, buildings and structures.

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